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Mover guide in a linear electric generator with double-sided stationary stators

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Abstract: This study addresses double-sided stationary stators in a linear electric generator with similar operation to a linear oscillatory motion electric machine. The plate mover in the linear electric generator's double-sided stationary stators is powered by the acoustic power output of the thermoacoustic engine's acoustic line. The main originality of this structure resides in the linear guidance used for the moving part. The mover is made up of a plate of sandwich magnets between two stators. This plate is in magnetic balance between the two stators through a controlled friction device.

1 Introduction

The double-sided linear electric generator is intended for use with an electroacoustic converter (Fig. 1). An electroacoustic machine converts acoustic energy into electrical energy, and vice versa converts electrical energy into acoustic energy. An acoustic wave is created as 'input' using an electromechanical transducer. This acoustic wave is amplified by the heat recovered as 'output' using a linear electric generator [1, 2].

The production of acoustic power is used to achieve cryogenic temperature ranges in thermoacoustic refrigerators, or to interface with reciprocating electroacoustic power transducers to generate electricity [3–5]. Linear displacement is generally limited to a few millimetres. Other examples for which it may be interesting to use

a linear electric generator include linear internal combustion piston engines and Stirling engines (Fig. 2). A linear internal combustion engine was proposed for hybrid electric vehicles. The Stirling engine has been used for spacecraft as well as residential electric energy generation.

The thermoacoustic engine converts heat into an acoustic pressure wave within the enclosures of insert gas, without any moving parts. This pressure wave is used to cycle a pair of electroacoustic power transducers, specifically a linear electric generator, to produce electrical output.

Though linear motion alternators with electromagnetic excitation were first proposed as single-phase synchronous generators, permanent magnet (PM) excitation has taken over more recently. Most competitive linear motion generators now rely on PMs. It is reasonable to classify linear motion generators into three categories: with a coil mover, with a PM mover and with an iron mover [7–10].

In these systems, special attention is paid to tribological aspects related to guiding the moving parts of the electromagnetic structure [11–15]. Our goal to eliminate the reaction force, at the friction surface level to obtain contact, ensuring the centring of the moving plate, but with reduced friction.

This device is a system to compensate for reaction force based on pressure screws acting on springs. The principle is to return the exact force of attraction between the mover and the stators thanks to an adjustable spacing force (the action of a set of pressure screws on springs) between the stators, as will explain in the following sections.

The advantages of the proposed PM linear electric generator over a traditional linear electric generator are its compactness, very high dynamic range due to the lightness of the moving part and greater efficiency.

2 Linear electric generator design

This section mainly discusses linear electric generator's double-sided stators operating similarly to linear oscillatory motion electric machines. Linear motion generators tend to be single-phase machines, because linear oscillatory motion imposes a change of phase sequence for the change in motion direction. A three-phase linear generator may be built from three single-phase linear generators, electrically phase-shifted by $2\pi/3$ and physically independent. Fig. 3 shows the structure chosen to implement the linear electric generator. Design specification data is given in Table 1.

The fixed parts (stators) of the linear electric generator are made of a magnetic circuit in an M300-35A rectangular form, in

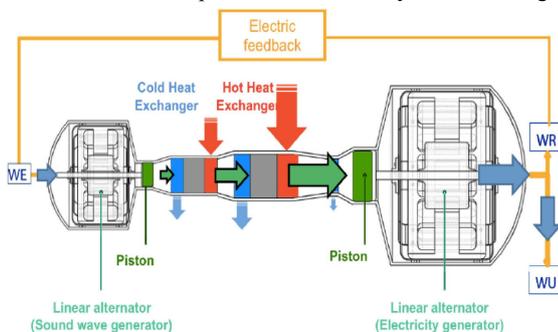


Fig. 1 Electroacoustic converter (thermoacoustic engine manufactured by Hekyom)

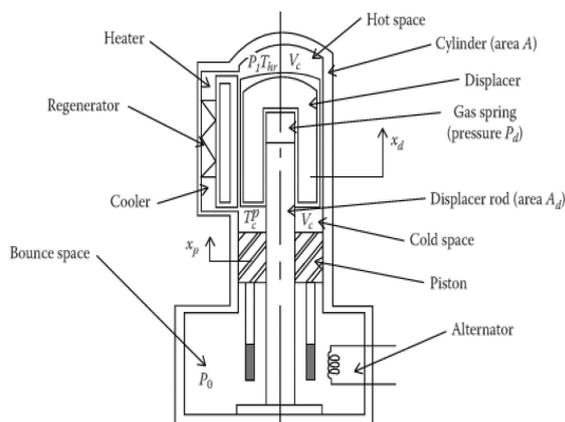


Fig. 2 Stirling engine – linear alternator [6]

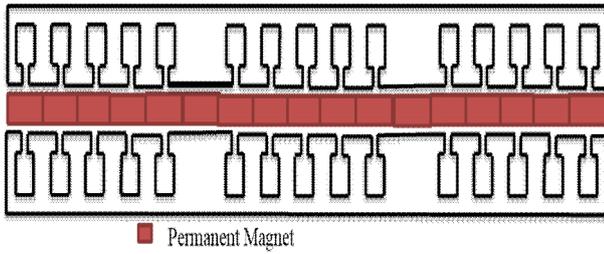


Fig. 3 Magnetic structure, three-phase linear generator

Table 1 Design specification data

Element	Symbol	Value, mm
slot opening height	—	1.0
slot wedge height	—	0.0
slot body height	—	5.0
slot opening width	—	0.5
slot wedge width	—	2.5
slot body bottom width	—	2.5
slot pitch	—	5.0
pole pitch	τ	5.0
PM length	—	5.0
PM thickness	h_m	3.0
air gap	g	0.3
generator length	—	230
generator width	—	50
stroke	L_s	20
PM mass		0.25875 kg
generator power		1 kW

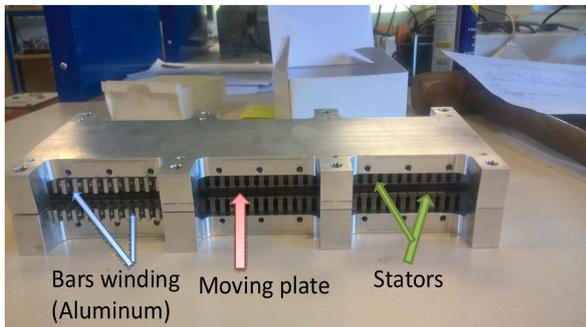


Fig. 4 Linear electric generator

laminated sheets equipped with the slots intended for three-phase winding aluminium bars.

The magnetic circuit is laminated in stacked plates cut to a thickness of 0.5 mm. The number of stacked plates is proportional to the width of the magnetic circuit. The plate is punch-cut in a single operation from a strip of sheet metal, first insulated on both sides by a phenolic class H varnish. The plate hole profile has a circle shape that will help stack plates for the appropriate height of the magnetic circuit to be dipped in the oven. The side of the plate bore has 36 slots intended to receive the winding bars after stacking.

The coil is a three-phase-series bar star. Each bar is composed of a rectangular aluminium section (7×2 mm) to ensure transverse field compensation of the Roebel slot process. Bar winding has several advantages over traditional winding: good slot filling factor (>80%), minimisation of solid insulation and the potential difference between bars, better performance, and good thermal behaviour in the slot.

The difficulty in carrying out winding with more than one layer and the additional losses are disadvantages because it is a low-voltage winding. The linear electric generator with double-sided stators is currently being built. Fig. 4 shows the various parts that have been made.

A linear electric generator with double-sided stators is protected by an aluminium cover, called enclosure, against ingress of moisture, dust, atmospheric impurities and any foreign materials.

The PM mover consists of a PMs made of NdFeB, which are magnetised in the transversal direction. The plate mover in the linear electric generator with double-sided stators is driven by acoustic power at the acoustic line output. Acoustic amplification is estimated by measuring the static acoustic pressure of the enclosures, the acoustic flow and the acoustic pressure at the acoustic line input and output. Acoustic performance of the line is linked to the three above-mentioned quantities. The expression of acoustic power is given by

$$P_{AC} = \frac{1}{2} Q p_{aco} \cos \rho \quad (1)$$

where P_{AC} is the acoustic power (W), Q is the acoustic flow (m^3/s), p_{aco} is the acoustic pressure and ρ is the phase shift between speed and pressure.

3 Plate mover displacement

The plate mover guide by the outer springs (Fig. 5) has the function of centring the plate mover so that it is free of mechanical friction and wear. The moving part of the generator consists of a plate of low thickness, obtained by assembling small magnets, to reduce inertia.

To preserve high thrust force density, in order to achieve a high power mass for the generator, it is essential to minimise the air-gap thickness. Therefore, taking the lack of rigidity of the plate mover into account, it is unrealistic to expect proper functioning without any intervention of the friction problems between fixed and moving parts. This phenomenon is amplified by the fact that it is not possible to introduce mechanical guidance elements between the plate mover and stators due to the small size and significant accelerations [6, 16–18].

The device is designed by tolerating mechanical contact between fixed and moving parts at the outset. The solution clearly works only if the contact forces are close to zero. Figs. 5 and 6 show the implementation of this guidance system and the means to achieve a contact force close to zero.

In Fig. 6, we assume that the different parts of the actuator are free in translation following the y direction. The PMs in the moving part of the actuator exert a magnetic attraction force, F_m , on the stator, which therefore comes to contact the friction surface. The reaction force, F_r , exerted on this surface is then equal to F_m . Regardless of the friction coefficient, the plate mover is blocked in translation because the friction force is very strong.

We therefore seek to eliminate the reaction force, F_r , at the friction surface level in order to obtain a contact that ensures the plate mover centring, but with reduced friction.

In Fig. 5, we present the device that compensates, and even cancels, friction forces that appear between the stators and the moving plate translation according to z .

We add a system of pressure screws acting on springs. These screws repeat the reaction forces.

The screws are tightened to maintain contact (mechanical gap zero). This action creates a compensation force, F_c , at the screws levels. With the stator in equilibrium, the sum of the applied forces is zero, and we can write

$$2\vec{F}_c + \vec{F}_m + \vec{F}_r = 0 \quad (2)$$

The reaction force, F_r , at the friction surface level becomes zero, when the following equation is obtained:

$$2\vec{F}_c + \vec{F}_m = \vec{0} \quad (3)$$

Equation (3) is obtained by adjusting compensation strength. If we can move towards $F_r=0$, the wear of the contact surface will be controlled under dynamic regime.

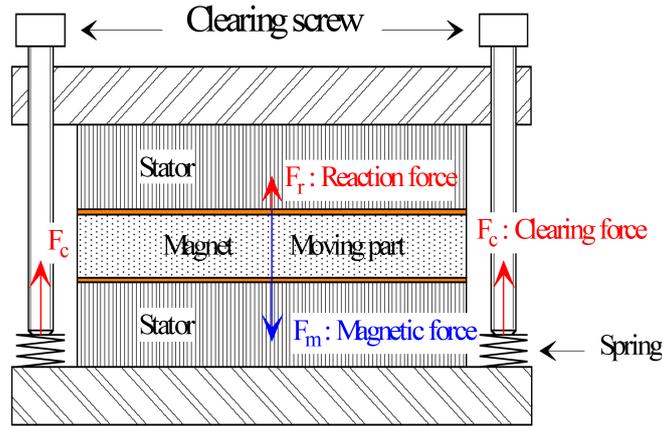


Fig. 5 Flat linear electric generator structure with guiding techniques

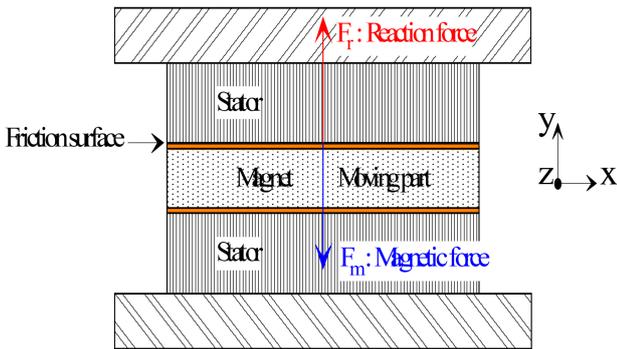


Fig. 6 Flat linear electric generator structure without guiding techniques

$$k = \frac{B^2 S_c}{4a \mu_0} \quad (6)$$

4 Sizing of the magnetic spring

For this application, we developed a magnetic spring that takes over the architecture of our linear actuator: A magnetic plate moves between two ferromagnetic stators (Fig. 7). The recalling force is created when the magnets deviate from the ferromagnetic part. Adequate sizing makes it possible to obtain substantially constant stiffness over the entire actuator stroke.

The plate mover is subjected to acceleration and deceleration phases. It is considered as a mass in linear oscillatory motion that undergoes accelerations and decelerations. Inertial force was born in the acceleration phase, resulting in an additional power, which is returned during the deceleration phase.

4.1 Force balance equation

An electromechanical system can be described simply with the help of the following force balance equation:

$$M \frac{d^2 x}{dt^2} + D \frac{dx}{dt} + kx = \pm F_e \pm F_{ch} \quad (7)$$

where M is the mover mass, D is the damping coefficient, k_m is the stiffness coefficient or magnetic spring constant, F_e is the instantaneous electromagnetic force developed, F_{ch} is the instantaneous external passive load, x is the displacement, $F_e > F_{ch}$ denotes acceleration and $F_e < F_{ch}$ denotes deceleration.

Assuming $D = 0$ and $k = 0$, the force balance (7) becomes

$$M \frac{d^2 x}{dt^2} = \pm F_e \pm F_{ch} \quad (8)$$

4.2 Acceleration phase

The force required for displacement (acoustic line – linear electric generator) is given by Newton's second law:

$$F(t) = M \ddot{a}(t) = M \frac{d^2 x}{dt^2} \quad (9)$$

where \ddot{a} is the acceleration (second derivative of position x) and M is the mass of the plate mover.

The work of the acceleration force is given by

$$dW = -F dx \quad (10)$$

$$\frac{dW(t)}{dt} = -M \frac{dv(t)}{dt} v(t) \quad (11)$$

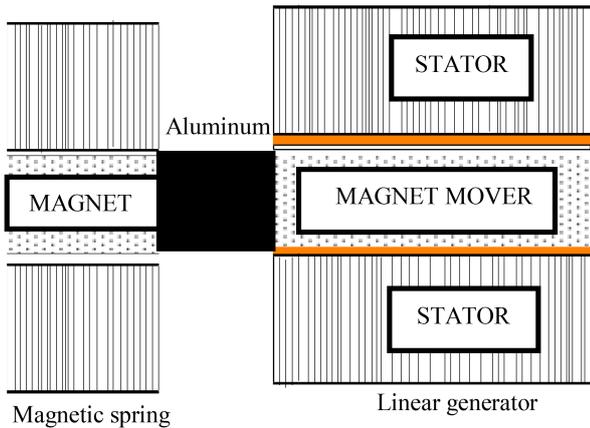


Fig. 7 Linear electric generator with magnetic spring

The force \vec{F}_m is collinear with the displacement direction z . It is applied perpendicularly to the air-gap surface, S_c , with air-gap flux density, \vec{B} . The norm of the force F_m exerted by the magnet is calculated by the following equation:

$$F_m = \frac{B^2 S_c}{2\mu_0} \quad (4)$$

Compensation force is calculated by the following equation:

$$F_c = ka \quad (5)$$

where k is the stiffness coefficient or spring constant and a is the compression stroke of the spring.

For an induction value B , obtainable for the M300-35A material, the value at the beginning of saturation, we obtain the value of k :

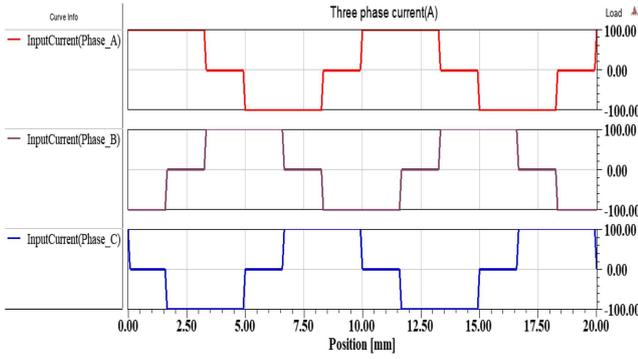


Fig. 8 Three-phase current versus position

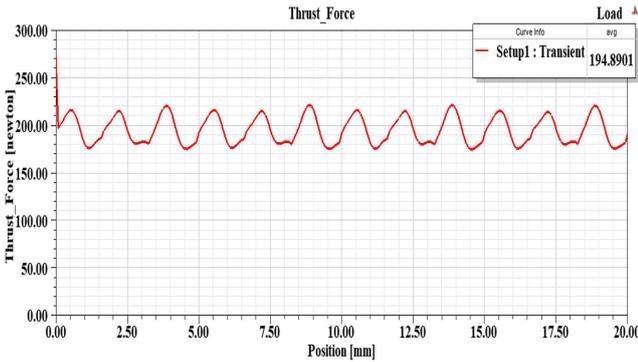


Fig. 9 Thrust force versus position

The negative sign is introduced because the inertia force opposes the displacement imposed by the acoustic line. The work of the force is achieved by integrating on a displacement corresponding to a time interval of a period $[0, T]$:

$$W(T) = -M \int_0^T \frac{dv(t)}{dt} v(t) dt \quad (12)$$

Inertial power at displacement is the derivative of energy:

$$P_I(t) = \frac{dW(t)}{dt} = -M \ddot{a}(t)v(t) \quad (13)$$

$$P_I(t) = M L_s^2 \pi^3 f^3 \sin(4\pi f t) \quad (14)$$

where M is the mass of the plate mover ($M=0.25875$ kg), calculated by finite elements; x is the Position, $x = 1/2L_s \sin(2\pi f t)$; L_s is the stroke ($L_s = 20$ mm) and f is the mechanical frequency ($f = 50$ Hz).

The maximum inertial power of 400 W is high for the linear generator studied.

4.3 Analytic method

The magnetic spring allows the inertial power of the plate mover stored during the deceleration phase to be restored during the acceleration phase. The frequency of resonance must be equal to that of the system.

The power returned or stored by a magnetic spring is given by (15):

$$P_{RE}(t) = v(t)f \quad f = kx(t) \quad (15)$$

$$P_{RE}(t) = \frac{1}{4} \pi f k L_s^2 \sin(4\pi f t) \quad (16)$$

where k is the magnetic spring stiffness constant.

The resulting power (P_R) is the difference between the inertial power and the compensation power of the magnetic spring:

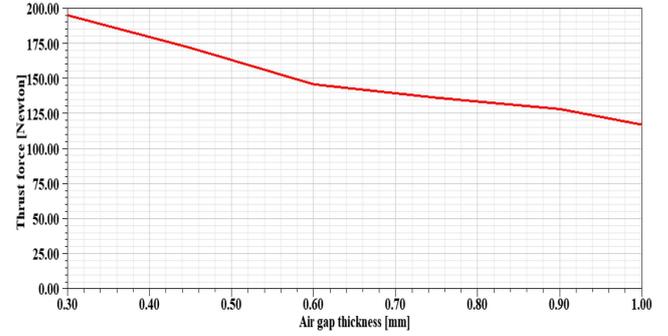


Fig. 10 Thrust force versus air gap thickness

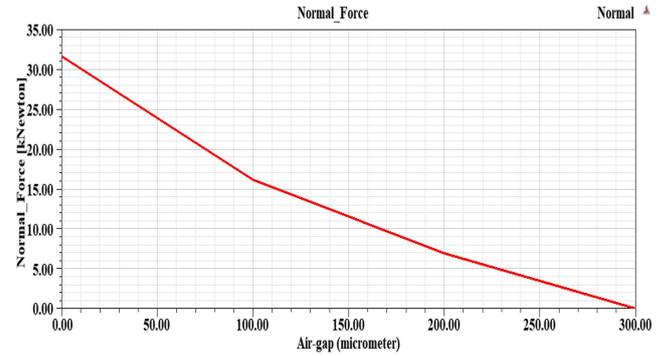


Fig. 11 Normal force versus air gap thickness

$$P_R(t) = P_I(t) - 2P_{RE}(t) \quad (17)$$

$$P_R(t) = \frac{1}{2} \pi f L_s^2 (2\pi f^2 M - k) \sin(4\pi f t) \quad (18)$$

The resulting peak power (P_{RC}) is obtained when $\sin(4\pi f t) = 1$, i.e. $t = T/8$:

$$P_{RC}(t) = \frac{1}{2} \pi f L_s^2 (2\pi f^2 M - k) \quad (19)$$

The thrust start-up force (F_D) is given by the following expression:

$$F_D = k \frac{L_s}{2} \quad (20)$$

5 Modelling forces using a finite element method (FEM)

Simulations are performed with the dimensions given in Table 1 for the flat linear electric generator with double-sided stators.

Given the current of each phase (Fig. 8), the fundamental steady-state characteristics are the thrust force versus displacement and versus air-gap thickness and the normal force versus air-gap thickness.

The thrust force versus displacement characteristic gives the relationship between the tangential force and displacement from the equilibrium position (Fig. 9).

The air-gap is a very important aspect a linear electric generator electromagnetic setting, as it affects the generator's performance. Thrust force decreases as the air-gap increases (Fig. 10).

The thrust force is very sensitive to small changes in the air-gap. The parasitic contact force between stators and the moving part depends on the air-gap, being strictly linked to the mutual position of all PMs and all windings (Fig. 11).

The mechanical air-gap is almost zero, because the fixed and moving parts are in contact, and the magnetic air-gap, corresponds to the thickness of layers of friction.

In practice, there is no perfect centring. The air-gap exists and a thrust force is created, giving rise to a normal force that influences the performance of the linear electric generator. The thicknesses of

the part and other plate movers are not identical, so we must introduce an offset (e_d).

We have $e_1 = e - e_d$ and $e_2 = e + e_d$ with e being the theoretical air-gap mechanics, e_1 the upper air-gap and e_2 the lower air-gap.

This asymmetric position generates a difference of strength that tends to press the plates against each other. This force is applied perpendicularly to movement and creates friction. The magnetic balance of the plates is very unstable.

6 Conclusion

This paper explains the friction compensation technique for a linear electric generator using the spring system, coupled with two-dimensional FEM, to design springs that compensate the friction force and the normal force versus air-gap thickness. It has been shown that the technique presented in this paper is effective for obtaining design springs to cancel the friction force for linear electric generators.

The proposed screws system concept is simple and applicable effectively to the linear electric generator to cancel friction force.

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